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by Amy Tank, Denis Rickman, Jay Ehrgott, Richard Pearson, and Jason Angel

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Results from the METB code and the experiments are compared. Initial comparisons between the code and experimental results demonstrate good correlation. Both experimental results and code predictions show that the cased charge is capable of producing heavy damage to the earth and timber bunker, provided that the charge is located so that the front wall of the bunker is near or within the crater the charge creates in the soil. The charge produces light damage to the bunker at further distances. The experimental results also show that the charge causes significant damage to the rear bunker wall via airblast loading, and this mechanism is capable of producing damage at greater distances than can the ground shock loading. The key airblast mechanism responsible for the rear wall damage is the positive pressure differential between the inside of the bunker and the exterior. This pressure reached values of 25.5 to 51.7 KPa. Such differential pressures were sufficient to severely damage the rear wall of the bunker.

15. SUBJECT TERMS
static cased charge, METB, earth and timber bunker, structural damage

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STATIC EXPERIMENTS OF PARTIALLY BURIED CASED CHARGES AGAINST EARTH AND TIMBER BUNKERS

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The US Army Research Laboratory (ARL), in conjunction with the Engineer Research and Development Center (ERDC), performed experiments to assess the effects of a partially buried charge against an earth and timber bunker. The experiments were designed to evaluate the ground shock and airblast environment, as well as the resultant loads on the bunker, produced by a cased charge with a TNT-equivalence of 41.4 Kg. ARL's Model of Earth and Timber Bunkers (METB) code was used to predict ground shock loads produced by the buried charges. The charges were placed at burial depths of 0.50 m or 0.91 m, and at varying distances from the bunker, corresponding to expected levels of no damage, light damage, and collapse as predicted by the code.

Results from the METB code and the experiments are compared. Initial comparisons between the code and experimental results demonstrate good correlation. Both experimental results and code predictions show that the cased charge is capable of producing heavy damage to the earth and timber bunker, provided that the charge is located so that the front wall of the bunker is near or within the crater the charge creates in the soil. The charge produces light damage to the bunker at further distances. The experimental results also show that the charge causes significant damage to the rear bunker wall via airblast loading, and this mechanism is capable of producing damage at greater distances than can the ground shock loading. The key airblast mechanism responsible for the rear wall damage is the positive pressure differential between the inside of the bunker and the exterior. This pressure reached values of 25.5 to 51.7 KPa. Such differential pressures were sufficient to severely damage the rear wall of the bunker.

INTRODUCTION

ARL was tasked to validate the shock prediction code METB, developed at ARL [1] to predict the ground shock loads produced by buried munitions. A set of six experiments was developed for the validation. METB was used prior to experiment execution to predict the level of structural damage to the earth and timber bunker that was expected. This report documents the METB predictions, the design of experiments, the experimental results, and the comparison between pre-test predictions and experimental results.

METB CODE PREDICTIONS

METB Background

METB is an empirical simulation of weapons effects on field fortifications. METB calculates the structural damage to earth and timber bunkers by warheads that detonate in or near the bunker's soil layer. The program's algorithm consists of two parts, one that models ground shock loading and one that models structural response of the bunker's wooden inner structure. The basic algorithms are derived from well-established manual design techniques covered in Department of Defense technical publication TM 5-855-1 [2].

The ground shock loading algorithm takes into account the high explosive charge mass, charge geometry, explosive type, soil type, the geometry of the soil layer, placement of the bunker structure and warhead relative to the soil layer. The 1-D model calculates stress and particle velocity as a function of radial distance from the charge. The model also accounts for the effects of tensile relief waves generated at the free boundaries of the soil layer and compressive waves generated at reflected boundaries. The model assumes the charge to be spherically symmetrical. The shape of the charge used in the experiments was generally cylindrical. To take into account the cylindrical shape of the warhead, the charge in the model was subdivided into a number of subsections, each of which was modeled as a spherical charge containing the appropriate mass of HE.

The structural response algorithm examines only one wall or the roof of the bunker at a time by decomposing the walls or the roof into a soil layer and the beams that comprise the inner wood support structure. The algorithm takes into account the dimensions of the beam, beam end conditions (fixed and free), Young's modulus, ultimate stress, density of the beam, density of the overlying soil layer, static loading from the weight of the soil layer, and dynamic loading from the detonation of warhead sections. The single degree of freedom algorithm calculates the uniform impulse required to deflect the center of the beam far enough to raise the stress at the center to the ultimate stress. If the ultimate stress is exceeded, the beam is considered failed. Since the loading on the beam is not uniform, a weighted average of the loads at several points on the beam is used to represent the uniform load.

The logic for assigning the level of bunker damage is built into the METB code. A beam with a damage level between 60 and 100% is assigned a damage value of 2. If the damage level is 100%, a damage value of 3 is assigned. METB only represents fixed and free support conditions. For beams with support conditions between fixed and free, the damage value is calculated to be the sum of the damage values from the code for both the fixed and the free case. If the sum is 5, the beam is considered moderately damaged. If the sum is 6, the beam is considered failed.

The damage level for the entire bunker is calculated as follows. If no beam suffered moderate damage or is failed, the bunker is considered to be undamaged. If one or more beams suffered moderate damage but less than 25% of the beams failed, then the bunker is considered to have suffered light damage. If more than 25% but less than 50% of the beams failed, then the bunker is considered to have suffered significant damage. If more than 50% of the beams failed, the bunker is considered to have collapsed.

Pre-Test Predictions

Pre-test predictions were conducted by ARL to determine the required placement of the cased charge relative to the bunker to obtain no damage, light damage, and collapse of the structure for the two different burial depths. The bunkers used for the validation experiments had

front walls comprised of 6 beams. Since the beams had end conditions somewhere between fixed and free, the structural response was calculated using both end conditions and the damage level for the bunker was calculated as the sum of the damage values from the fixed and free conditions. The pre-test prediction is given in Table 1.

Table 1. Pre-Test Prediction of Distance to Bunker Required for a Given Damage Level

Experiment Number	Depth of Burial (m)	Distance to Bunker (m)	Expected Bunker Damage Level
1	0.50	6.5	No Damage
2	0.50	4.0	Light Damage
3	0.50	2.0	Collapse
4	0.91	7.0	No Damage
5	0.91	6.0	Light Damage
6	0.91	2.7	Collapse

EXPERIMENTAL PLAN

Experiment Configurations

The experiments were designed by ARL and ERDC to evaluate the ground shock and airblast environment produced by a statically emplaced cased charge in a well-controlled sand backfill as well as the resultant loads on earth and timber bunkers placed in this same backfill. The cased charges had a TNT-equivalence of 41.4 Kg. For all experiments, the charges were placed in a vertical, nose-down orientation. The charges were tail-initiated with a cast booster.

Six experiments were performed for METB code validation purposes. The experiments were conducted in accordance with the METB pre-test predictions. The charge depth of burst (DOB) and charge to bunker stand-off for each experiment are given in Table 2.

Table 2. Experiment Matrix

Experiment Number	Depth of Burial (m)	Distance to Bunker (m)	Expected Bunker Damage
1	0.50	6.52	No Damage
2	0.50	4.02	Light
3A	0.52	2.04	Collapse
4	0.91	6.98	No Damage
5	0.91	6.04	Light
6	0.91	2.84	Collapse

On each experiment, an array of measurements were placed to capture the airblast environment on the ground surface, airblast pressures inside the bunker, the ground shock environment, and the response of the bunker. A typical measurement array is shown in Figure 1.

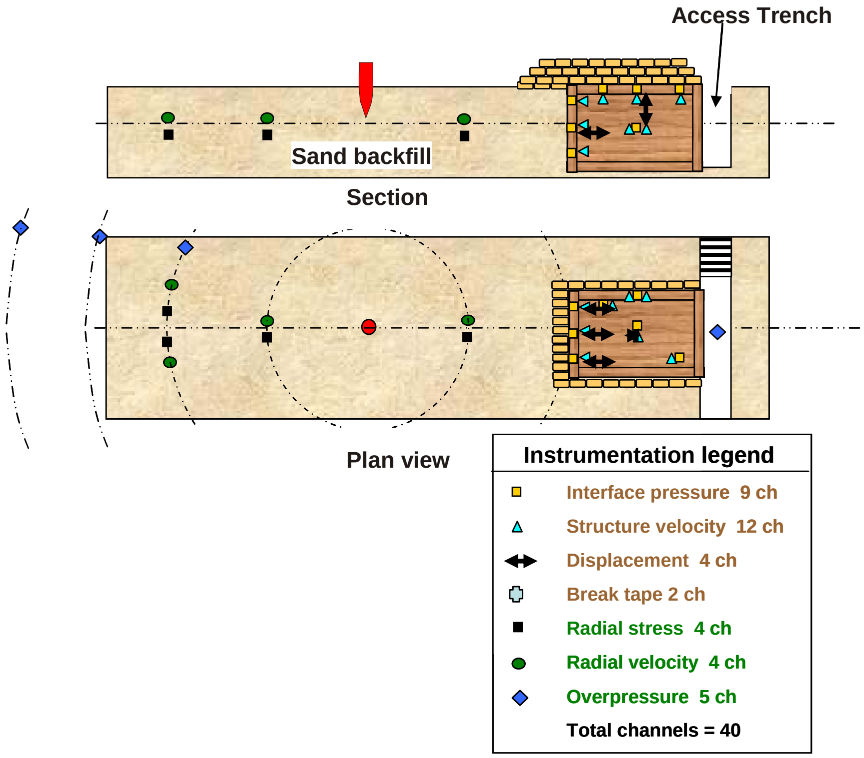

Figure 1. Typical measurement array for buried bunker experiments

Earth and Timber Bunker

All experiments used an earth and timber bunker as the target. The bunkers were approximately 2.4-m long by 3.0-m wide by 2.4-m high and constructed of no. 2 yellow pine lumber. The bunkers were placed in a sand backfill that surrounded the front and sides. The rear of each bunker was connected to a section of a timber-lined trench that provided access into the bunker. A layer of sand, confined within a perimeter wall of sandbags, was placed over the bunker roof.

Soil Backfill

Dry flume sand was selected as the backfill soil for all experiments. The properties and shock responses for this sand type are well documented. The material is classified as poorly graded sand (SP) according to the Unified Soil Classification System [3].

For all experiments, the total backfill depth was approximately 2.7 m, and the backfilled area width was 4.9 m. This allowed a 0.5-m-thick layer of sand backfill to be laced beneath the bunker and a 1.2-m width of soil to be placed on both sides of the target bunker. The length of the backfilled area varied as needed for each experiments so as to encompass the cased charge and to provide an uninterrupted soil backfill between the cased charge and the target bunker.

The sand was placed in approximately 8-inch thick lifts and compacted with a minimum of three passes with a vibratory plate compactor. In each lift, the quality control inspector made three to four measurements of wet soil density and water content with a nuclear moisture-density gage and obtained three to four samples of the sand from the mid-depth for the determination of microwave and standard oven-dry water contents. Determination of acceptance or rejection of each lift was based on the calculations of the mean dry density and

water content. Adjustments were made to the lift when variations outside the set limits were found. Laboratory material property tests were conducted on samples of the flume sand. Recommended compressibility and strength relations were developed based on the results of these tests.

EXPERIMENTAL RESULTS

The experiments were conducted by ERDC at the Range 19 Test site, Ft. Polk, LA. Experiments 1, 2, and 5 were successfully conducted as planned. During the execution of Experiment 3, a fragment from the cased charge severed the power cables to the test range resulting in a loss of recorded instrument experimental data. Experiment 3 was repeated and is labeled as Experiment 3A. Experiments 4 and 6 were combined into a single event. A description of each experiment is given below. A figure is also provide for each experiment that depicts the damage to the bunker, the peak airblast overpressures, the peak interface stress and horizontal velocity measured at the front wall, the crater profile, as well as the peak pressures inside the bunker and trench for experiments 2 - 6 [4,5].

<u>Experiment 1</u>

The cased charge in Experiment 1 was initiated 6.5 m from the bunker with a DOB of 0.50m. As expected, the detonation produced only minor damage to the target bunker. None of the front wall beams were damaged. The damage that the bunker suffered was observed on the back wall. Four of the rear wall beams were blown off. In addition, two of the vertical supports on the rear wall suffered sever damage.

Figure 2 depicts the results from the experiment. It was theorized that the damage may be related to airblast loading since the bunker was subjected to only modest ground shock loads. Because of this, airblast measurements were recorded inside the bunker and trench on subsequent experiments.

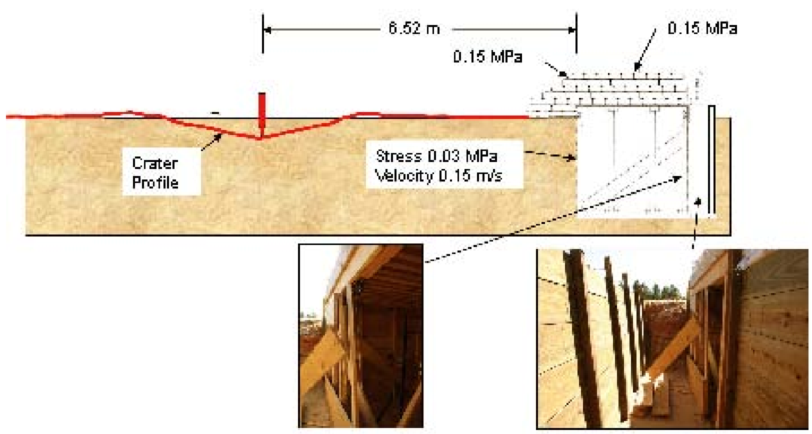

Figure 2. Results from Experiment 1

<u>Experiment 2</u>

In Experiment 2, the charge was detonated 4.02 m from the bunker at a DOB of 0.50m. Similar to Experiment 1, only the rear wall of the bunker sustained noticeable damage. All of the wooden beams were blown off and three of the vertical support timbers were broken.

Figure 3 depicts the results of the experiment. Air blast measurements in the bunker recorded a peak pressure of 0.028 MPa, while the peak pressure in the trench was 0.079 MPa. The failures observed in the rear wall of the bunker with beams displaced outwardly are indicative of an internal pressure loading. By examining the differential pressure between the bunker and the trench, an internal pressure of 0.038 MPa is calculated. This is enough pressure to produce the type of failure seen at the rear wall of the bunker. Pressure wave forms for the trench and bunker and the wave form for the differential pressure inside the bunker are given in Figure 4.

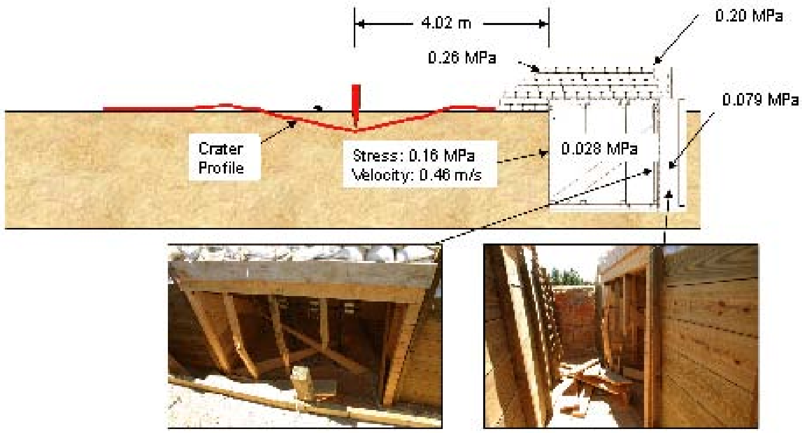

Figure 3. Results from Experiment 2

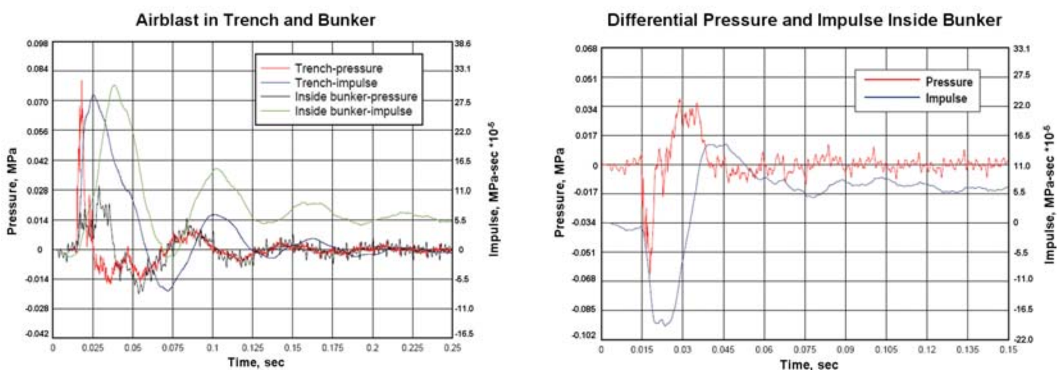

Figure 4. Pressure Measurements in the Trench and Bunker for Experiment 2

Experiment 3A

The distance from the cased charge to the bunker was 2.04 m and the DOB was 0.5 m for Experiment 3A. As expected, the bunker suffered significant damage. The front side of the bunker was very close to the leading edge of the detonation crater which caused damage to three of the beams and two of the front wall vertical supports. The peak stress measured at the front wall was 1.5 MPa. The rear wall of the bunker was also damaged; all of the beams were blown off, three of the four rear columns were removed, and the support header was destroyed. The failures observed in the rear wall of the bunker are indicative of an internal pressure loading which was determined to be 0.052 MPa based on the pressure differential between the bunker and the trench. Results from Experiment 3A are presented in Figure 5.

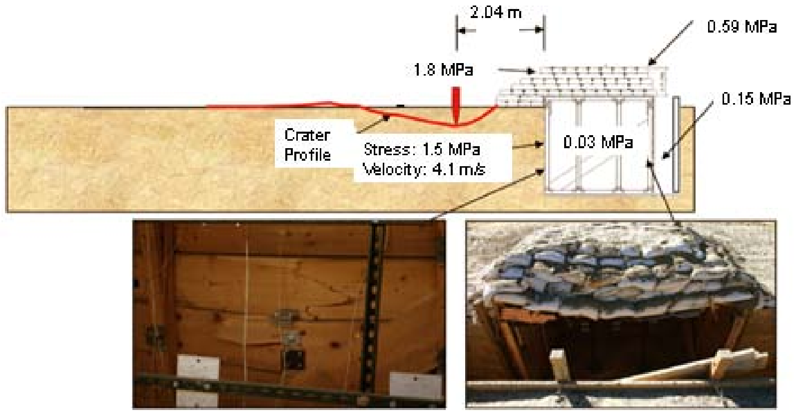

Figure 5. Results from Experiment 3A

Experiment 4

Experiment 4 was the first of the deeper burial depth. It was conducted at a DOB of 0.91 m and a charge to bunker distance of 6.98 m. Figure 6 presents the results from this experiment. As expected, no damage was observed on the front wall of the bunker. The rear wall sustained significant damage due to airblast. All of the wooden beams were blown off, and one of the vertical supports was broken. The peak differential pressure was 0.02 MPa.

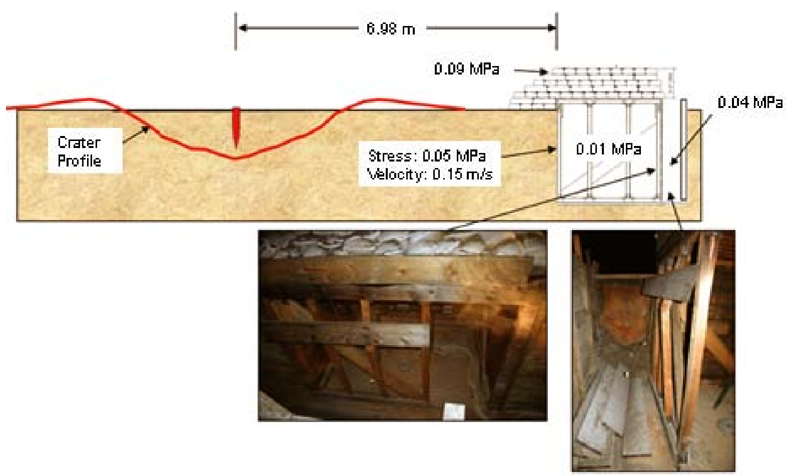

Figure 6. Results from Experiment 4

Experiment 5

Experiment 5 was also conducted at a DOB of 0.91 m, but the charge to bunker distance was 6.04 m. Once again, the rear wall of the bunker sustained significant damage in the form of several wooden plans blown off the wall. One of the vertical supports on the rear wall was also broken. These failures are indicative of an internal pressure loading. The peak differential pressure in the bunker was approximately 0.03 MPa. The front wall of the bunker did not sustain any observable damage. Results from Experiment 5 are given in Figure 7.

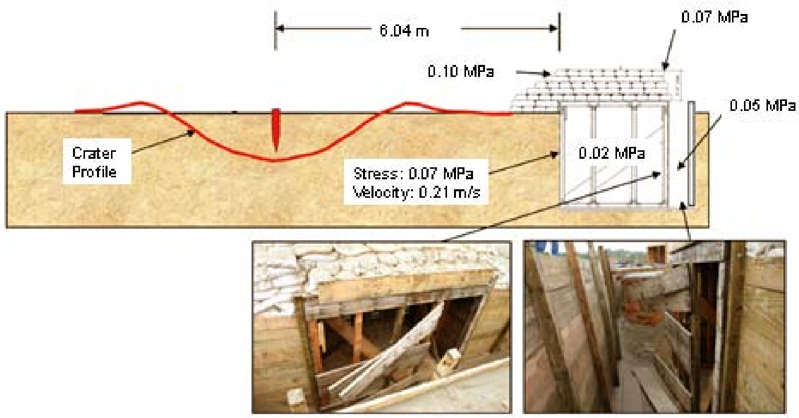

Figure 7. Results from Experiment 5

Experiment 6

For Experiment 6, the charge to bunker distance was 2.84 m and the DOB was 0.91 m. The front side of the bunker was just outside the leading edge of the detonation crater which caused damage to the front wall of the bunker. Four of the wood beams that comprise the front wall were broken, and one front wall vertical support post was broken at the connection. The peak stress on the front wall was measured to be 2.79 MPa. The rear wall of the bunker also sustained significant damage with all of the wooden beams blown off, and one of the vertical supports severely cracked. Again the failures observed in the rear wall are indicative of an internal pressure loading. The peak differential pressure was calculated to be 0.03 MPa. A depiction of the results is given in Figure 8.

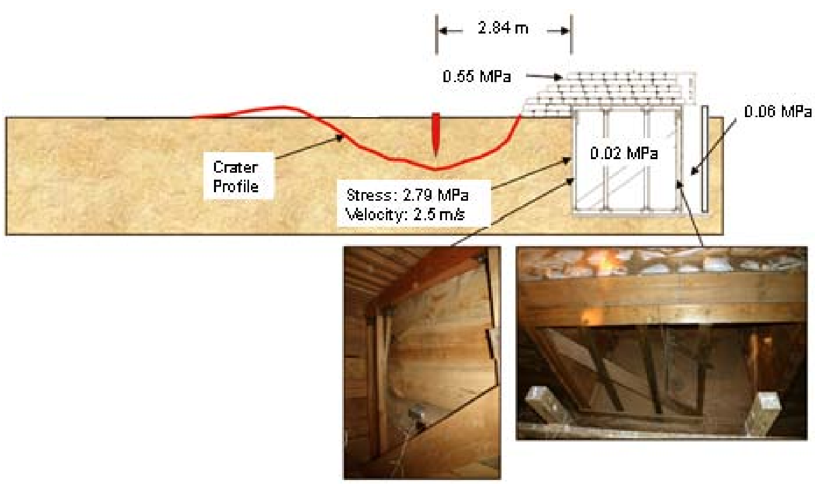

Figure 8. Results from Experiment 6

Further insight into the rear wall failure is provided in Figure 9, which compares the displacement of the rear wall and the pressure records. From this comparison, it is clear that the rear wall initially deflects inward due to the positive pressure condition in the trench. Rear-wall deflection reverses quickly after a significant positive differential pressure is developed inside the bunker. This provides compelling evidence that the rear bunker wall failure observed on all of the experiments is directly related to airblast/pressure loading.

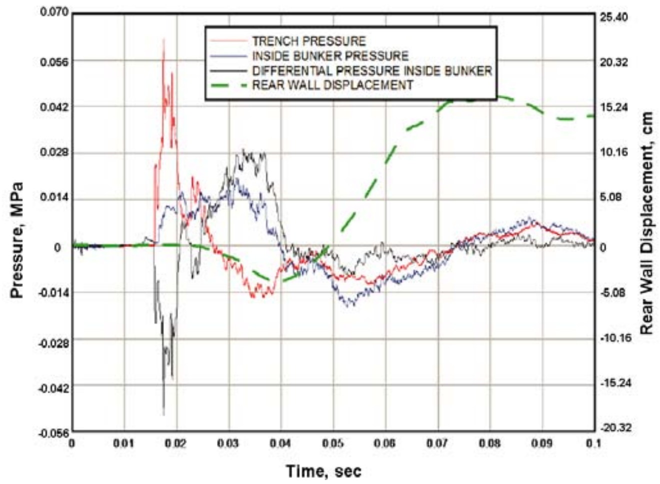

Figure 9. Comparison of Pressure Loading and Rear Wall Displacement

COMPARISON OF METB AND EXPERIMENTAL RESULTS

ARL conducted a comparison between measured values from the experiments and results from METB calculations. The following discussions address comparisons of the METB output to the measured ground shock environment and the METB predictions of structural damage to the observed levels of damage sustained by the earth and timber bunkers.

<u>Comparison of Ground Shock Loading</u>

Figures 10 through 12 show a comparison between the radial soil stress measured on the experiments and post test modeling. In Figure 10, the initial predicted peak stress agrees reasonably well with the experimental measurement. However, the tensile relief wave from the surface of the soil appears to be too strong and causes the modeled stress to drop below the experimental value after 10 milliseconds. The tensile wave from the soil surface also causes the mismatch between experimental and measured radial stress impulse. Figures 11 and 12 show similar results. The early tensile wave in the model is too strong driving the stress negative, but the later stages of the stress history are a reasonable match to the experimental data. Some adjustments in modeling the tensile wave generated at the soil air interface would probably improve the accuracy of the loading predictions [6].

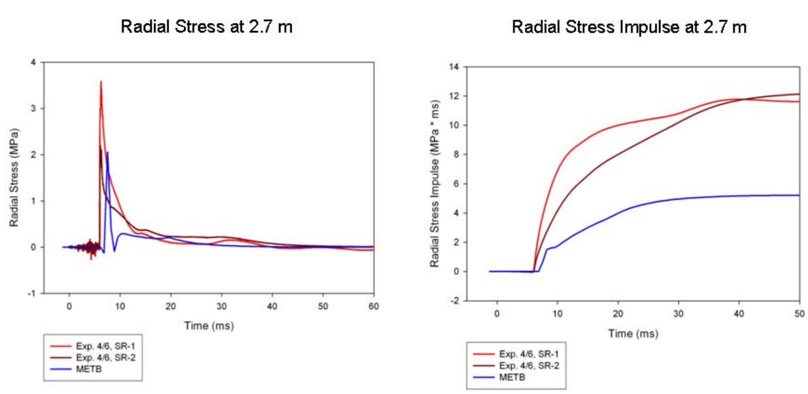

Figure 10. Comparison of METB and Experiment 4/5 Results for Radial Stress and Radial Stress Impulse at 2.7 m

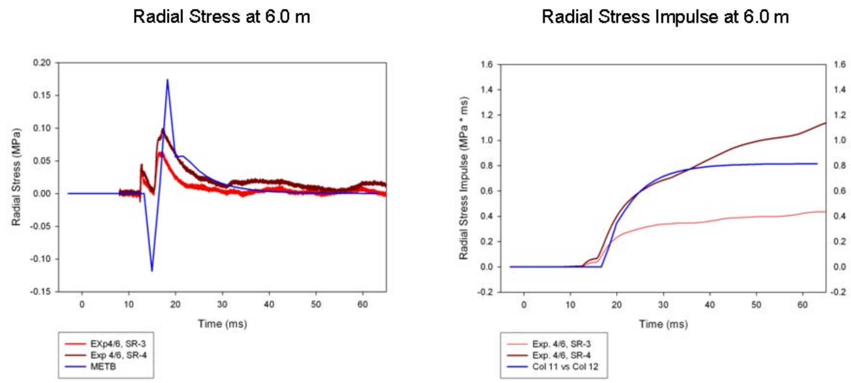

Figure 11. Comparison of METB and Experiment 4/5 Results for Radial Stress and Radial Stress Impulse at 6.0 m

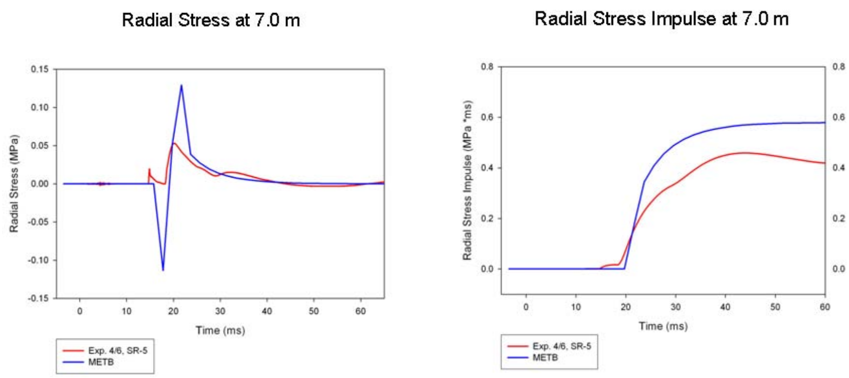

Figure 12. Comparison of METB and Experiment 4/5 Results for Radial Stress and Radial Stress Impulse at 7.0 m

Comparison of Structural Response

METB was developed to provide predictions of structural response of field fortifications to ground shock loading. Based on the experimental results, the majority of the damage to the bunker was due to air blast loading on the rear wall. This is because the rear wall of the bunker was not protected by sand bags or a soil layer like the rest of the structure making it particular vulnerable to damage. However, METB was not designed to model air blast loading. As a result, comparisons between METB and the experiments are limited to only the structural damage of the front wall of the bunker. Table 3 provides a comparison of structural damage to the front wall of the bunker according to the METB pre-shot predictions, the METB post-shot analysis, and the experimental results.

The pre-shot predictions were used to design the experiments. The distances from the charge to the front wall of the bunker were adjust to produce thresh hold damage, slight damage and bunker collapse. For practical reasons the actual experiment geometry had to be changed slightly. Post test modeling was carried out using the actual experimental geometry.

Post test modeling of experiment 3A predicted that two beams would be damaged and three would fail. In the experiment, three beams failed. In Experiment 6, METB predicted significant damage to five beams but no beam failure. In the experiment, four beams failed. In the other experiments, post test modeling predicted no significant damage to the beams and none occurred. The results indicate that METB can provide a reasonable first order estimate of damage due to ground shock.

Table 3. Comparison of Structural Response, METB Predictions and Experimental Results for the Front Wall of the Bunker

Experiment Number	Depth of Burial	Distance to Bunker	Pre-Shot METB Prediction of Expected Bunker Damage	Post-Shot Modeling Number of Front Wall Beams Predicted to be Moderately Damaged	Post-Shot Modeling Number of Front Wall Beams Predicted to Fail	Number of Front Wall Beams Failed in Experiment
	(m)	(m)				
1	0.50	6.52	No Damage	0	0	0
2	0.50	4.02	Light	0	0	0
3A	0.52	2.04	Collapse	2	3	3
4	0.91	6.98	No Damage	0	0	0
5	0.91	6.04	Light	0	0	0
6	0.91	2.84	Collapse	5	0	4

CONCLUSION

Air blast was the major damage mechanism for the bunker design used in the experiment. An unprotected rear wall proved particularly susceptible to differential pressure loading between the inside and outside of the bunker. Modeling this type of damage would have to be done with codes other than METB.

The ground shock stress calculated by METB provides a reasonable estimate of the loading on the bunker but over estimated the influence of the tensile stress wave generated at the soil's upper surface. The loading algorithm should be modified to limit the strength of these tensile waves.

METB is capable of providing a reasonable first order estimate of structural damage due to ground shock, but the model could be improved. The model assumes uniform loading across structural components when modeling their response. The loading model shows that for the ground shocks of interest in these experiments the loading can vary significantly over the length of a component. A simplified finite element algorithm using brick elements could use the available detailed loading information and might produce better estimates of structural response.

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